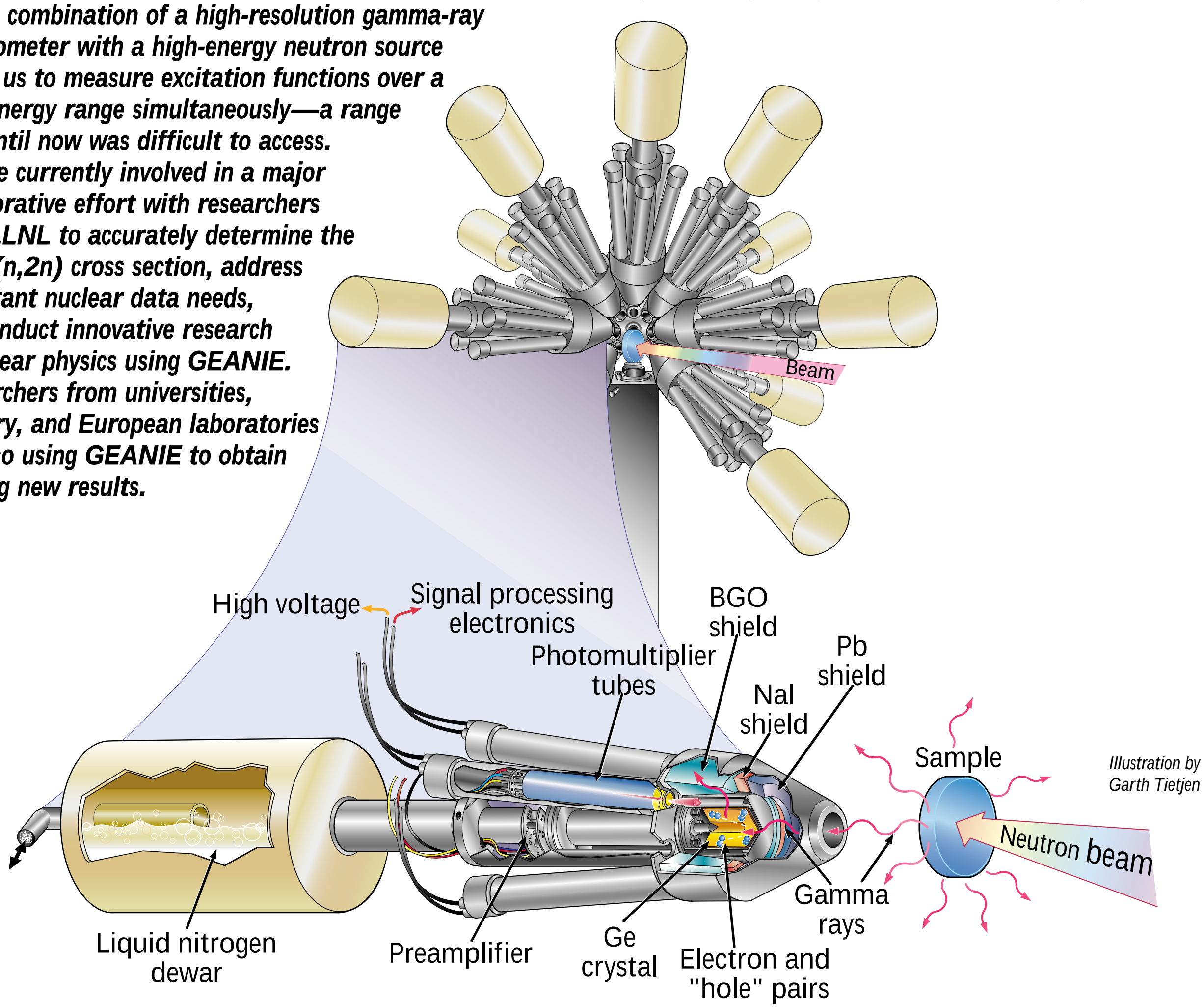
Advances in Nuclear Physics Research with GEANIE at the Weapons Neutron Research Facility

The large, high-resolution gamma-ray detector array GEANIE (GErmanium Array for Neutron-Induced Excitations) at LANSCE has been developed and commissioned as a powerful new tool for nuclear physics research in a major collaborative effort between Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory. GEANIE uses the pulsed, high-energy, white-spectrum neutron source at the Weapons Neutron Research (WNR) facility[1] for experiments aimed at gaining a better understanding of radiochemical data from past Nevada Test Site experiments for the Stockpile Stewardship Program, for research involving the Accelerator-Driven Transmutation of Waste (ATW) project, and for opportunities to explore new regions of excitation in basic nuclear physics. This unique combination of a high-resolution gamma-ray spectrometer with a high-energy neutron source allows us to measure excitation functions over a wide energy range simultaneously—a range that until now was difficult to access. We are currently involved in a major collaborative effort with researchers from LLNL to accurately determine the ^{239}Pu(n,2n) cross section, address important nuclear data needs, and conduct innovative research in nuclear physics using GEANIE. Researchers from universities, industry, and European laboratories are also using GEANIE to obtain exciting new results.

GEANIE Configuration

Presently, GEANIE consists of 20 bismuth germanate escape-suppression shields that surround 20 germanium (Ge) detectors and an additional 6 unsuppressed Ge detectors for coincidence studies (Fig. 1). GEANIE was built using elements of the High-Energy Resolution Array that was developed by the nuclear structure group at Lawrence Berkeley National Laboratory.[2] The original coaxial Ge detectors have been augmented by the addition of 11 planar Ge detectors. The combination of both coaxial and planar germanium detectors provides a powerful spectrometer for a wide range of experiments. The coaxial detectors have a useful gamma-ray detection range to several MeV. The planars are especially useful at lower gamma-ray energies and have extremely good



▲ Fig. 1. Cutaway view of GEANIE. Gamma rays produced from reactions in the target enter the detectors and, by a series of interactions, deposit their energy in the germanium (Ge) crystals. An electric signal proportional to the energy deposited is created in the Ge crystal and then amplified and digitized. The distinguishing characteristic of the Ge detector is its excellent gamma-ray energy resolution. Events in which some energy is lost from the Ge crystal are detected in the bismuth germinate (BGO) and sodium iodide (NaI) scintillator shields. Rejection of these events reduces unwanted background in the gamma-ray energy spectra obtained from the Ge detectors.

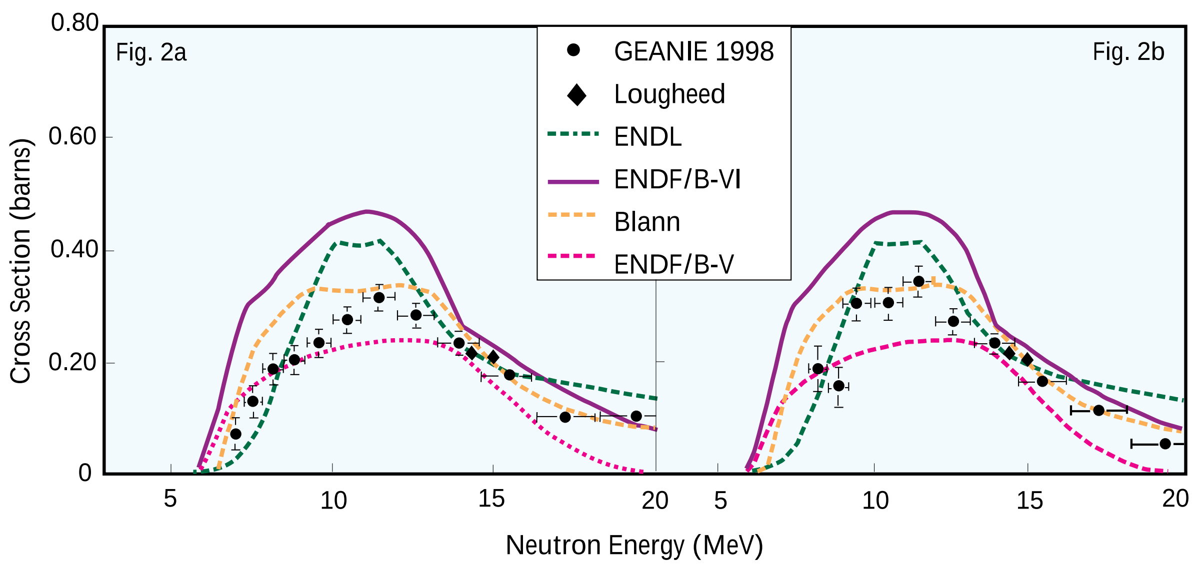
energy resolution. Incident neutron energies are determined using time-of-flight (TOF) techniques. GEANIE is located 20 m from the neutron production target.

GEANIE has a number of characteristics important for nuclear spectroscopy, including high-energy resolution (~0.2%), good efficiency, escape suppression for background reduction, and high granularity. Measuring characteristic gamma rays from neutron-induced reactions allows researchers to determine both the reaction channel—for example, (n,2n) or (n,3n)—and the particular level excited in the product nucleus. In addition, the reaction thresholds and cross-section peaks observed in excitation functions provide information for the identification and study of the various reaction products. The high neutron energies available offer many possible reactions, including inelastic scattering, multiple-neutron emission, proton emission, alpha emission, combinations like two-proton plus three-neutron emission, and fission.

Obtaining More Accurate Cross-Section Measurements

GEANIE is being used to obtain an accurate measurement of the ^{239}Pu(n,2n)^{238}Pu reaction cross section to help us better understand the radiochemical data from past Nevada Test Site experiments. From measured gamma-ray production cross sections, we obtain an estimate of total reaction cross sections as a function of incident neutron energy. By combining our results with calculations from the coupled pre-equilibrium and Hauser-Feshbach computer program GNASH,[3] we can use theory to account for the fraction of the cross section that is not measured with our technique. Fig. 2 shows preliminary excitation functions for the ^{239}Pu(n,2n)^{238}Pu reaction deduced from the partial gamma-ray cross sections for the 6^+ to 4^+ and the 8^+ to 6^+ transitions in ^{238}Pu. The ability to simultaneously measure excitation functions for many gamma-ray transitions provides checks for validation of the data and models used in the GNASH code. In addition, we are studying (n,xn) reactions on ^{235}U and ^{238}U to check our technique and to learn more about these nuclei.

The use of gamma rays is an important tool for (n,xn) measurements on actinide nuclei because the production of neutrons from fission interferes with a direct measurement of the (n,xn) neutrons. The GEANIE detectors have a good peak-to-total ratio that allows the resolution of individual gamma-ray lines above the background from fission and other gamma rays. The planar detectors play an especially important role in these measurements because they have excellent energy resolution and are relatively insensitive to neutrons. This is the first time that an array of planar germanium detectors has been used to study actinide nuclei. Fig. 3 shows a three-dimensional plot of data from the planar detectors taken with a ^{238}U sample. The plot shows the separation of gamma rays from inelastic scattering and (n,3n) reactions that differ in energy by less than 1.3 keV.



▲ Fig. 2. Preliminary ^{239}Pu(n,2n) cross sections, 1998-1999 data. Excitation functions for the (n,2n) reaction deduced from the 158-keV 6^+ to 4^+ (Fig. 2a) and the 210-keV 8^+ to 6^+ (Fig. 2b) transitions in the ^{239}Pu(n,2n)^{238}Pu reaction. The data have been normalized to the 13.8-MeV data point of Lougheed. ENDL, ENDF/B-V and VI, and Blann evaluations are shown for comparison. The data are preliminary pending further work on the efficiencies, attenuation factors, and other corrections to establish the absolute normalization accurately. No previous evaluation matches the data over the entire energy range.

Neutron-induced gamma-ray measurements provide a means to study nuclei through (n,xn) reactions (where x = 1, 2, 3 ...), probing nuclei that are otherwise difficult to access. Our previous experiments[4] with a single unsuppressed germanium detector in which we observed reactions on ^{208}Pb up to (n,9n) laid some of the groundwork for current studies. But with GEANIE, the ability to measure gamma-gamma coincidences opens up a much wider range of possible research.

Pursuing Physics Research with GEANIE

One area of research currently under way is the exploration of the excited states of nuclei in the mass 90–112 region. Interest in this mass region has been spurred by the recent observation of mixed-symmetry states in ^{94}Mo.[5,6] From only a short run on GEANIE, we have already identified twenty new levels in ^{92}Mo that will aid in searches for mixed-symmetry states,[6] although more detailed spectroscopic experiments remain to be done. In addition the reaction dynamics of neutron scattering from ^{92}Mo is being investigated in collaboration with Mark Chadwick and Phil Young from T-2.

In collaboration with researchers from Bruyères-le-Châtel and Saclay, we have been developing experiments to study fission fragments from both high-energy neutron-induced fission and spontaneous fission. By observing both the gamma rays (to determine the mass) and x-rays (to determine the charge), we hope to improve the knowledge of the fission process and study neutron-rich nuclei produced by fission. Current interests include fission fragment mass and charge distributions and a search for isomeric states in fission fragments.[7]

The isomeric first excited state of ^{235}U at an excitation energy of 77 eV with spin and parity $1/2^+$ is currently being investigated. Because of the extremely low excitation energy of the ^{235}U first excited state, our experiments cannot distinguish decays to the first excited state from decays to the ground state directly from the gamma-ray energy. However, we can often determine whether the ground or first excited state is populated from a knowledge of the spins of the states and gamma-ray multipolarities. We plan to estimate the population of this isomer relative to the ground state by neutron inelastic scattering.

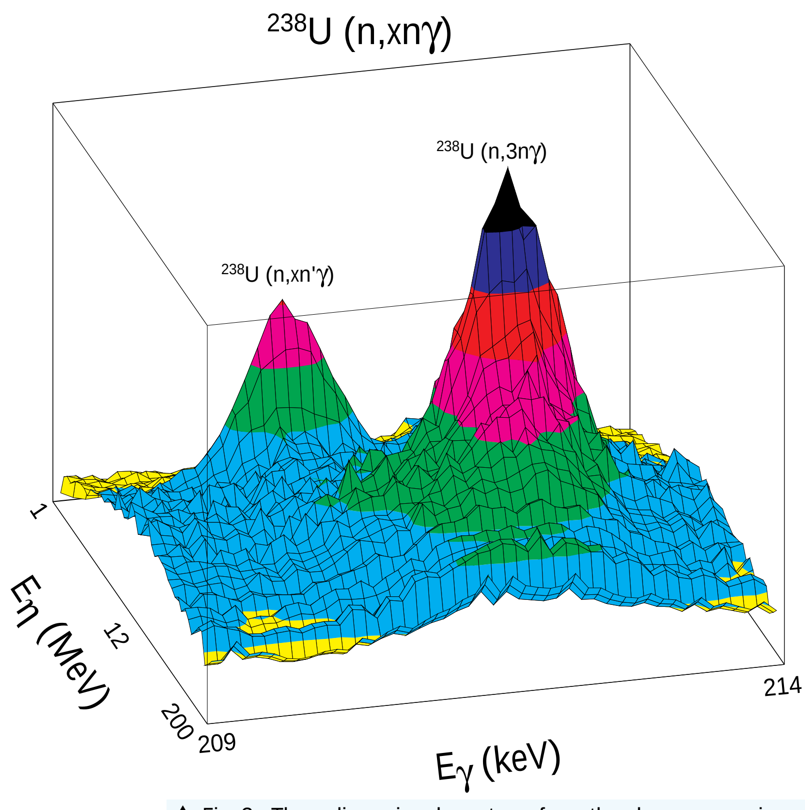
Off-line experiments using radioactive samples are conducted when the accelerator is not in operation and when upgrades and modifications to GEANIE are not in progress. In the last year, scoping studies of ^{252}Cf spontaneous fission have been conducted, and further spontaneous fission studies are planned.

References

1. P. W. Lisowski et al., "The Los Alamos National Laboratory Spallation Neutron Source," Nuclear Science and Engineering **106**, 208 (1990).

2. F. S. Stephens, "Spectroscopy of the Highest-Spin States," in Proceedings of the *International Symposium on In-Beam Nuclear Spectroscopy* (Akadémiai Kiadó, Budapest, 1984), p. 205.

3. P. G. Young, E. D. Arthur, and M. B. Chadwick, "Comprehensive Nuclear Model Calculations: Introduction to the Theory and Use of the GNASH Code," Los Alamos National Laboratory report LA-12343-MS (July 1992).



▲ Fig. 3. Three-dimensional spectrum from the planar germanium detectors showing the measured 8+ to 6+ transitions in ^{238}U and ^{236}U near 212 keV. The two gamma-rays differ in energy by less than 1.3 keV. The plot covers the neutron energy range from 1 MeV to 200 MeV. The different thresholds for the two reactions [inelastic and (n,3n)] are evident in the plot.

4. H. Vonach et al., "^{207,208}Pb(n,xng) Reactions for Neutron Energies from 3 to 200 MeV," Physical Review C **50**, 1952 (1994), and A. Pavlik et al., "^{27}Al(n,xg) Reactions for Neutron Energies from 3 to 400 MeV," Physical Review C **57**, 2416 (1998).

5. N. Pietralla et al., "Transition Rates between Mixed Symmetry States: First Measurement in ^{94}Mo," Physical Review Letters **83**, 1303 (1999).

6. P.E. Garrett et al., "States in ^{92}Mo Observed in the (n,n'g) Reaction with Spallation Neutrons," submitted to Physical Review C.

7. G.D. Johns, R.O. Nelson, W.S. Wilburn, D.M. Drake, D.E. Archer, J.A. Becker, L.A. Bernstein, P.E. Garrett, P.D. McNabb, W. Younes, Th. Ethvignot, and Th. Granier, "High-Energy Neutron-Induced Fission: Charge Yield Distributions and New Isomer Search and Spectroscopy," Second International Conference on Fission and Neutron-rich Nuclei, St. Andrews, Scotland, Los Alamos National Laboratory report LA-UR-99-2001.

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